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SMALL-SCALE EXPLOSIVE SEAM WELDING

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### SUMMARY

This report describes a unique small-scale explosive seam welding technique that offers improvements over conventional explosive welding techniques. This technique has successfully joined a variety of aluminum alloys and alloy combinations in thicknesses to 0.125 inch, as well as titanium in thicknesses to 0.056 inch. The explosively welded joints are less than one-half inch in width and apparently have no long-length limitation. The "ribbon explosive" developed in this study contains very small quantities of explosive encased in a flexible thin lead sheath.

The evaluation and demonstration of this welding technique was accomplished in three phases: evaluation and optimization of ten major explosive welding variables, the development of four weld joints, and an applicational analysis which included photomicrographs, pressure integrity tests, vacuum effects, and fabrication of some potentially useful structures in aluminum and titanium.

This joining technique can complement existing fabrication techniques through its simplicity and the ability of producing low-cost joints with strengths up to that of the parent metal. A major disadvantage of this welding technique presently is the reservation in using explosives. Other disadvantages are the destructive mechanical shock produced by the welding operation, and sharp notches at joint interfaces creating stress concentrations.

### INTRODUCTION

Explosive welding, which was first demonstrated in the early 1950's, can accomplish metallurgical bonds that are impossible to achieve by any other joining process, while maintaining material properties. Research in this area is presently being conducted by a variety of organizations: The Denver Research Institute (University of Denver and Martin-Marietta), Battelle Memorial Institute, Dupont, E. F. Industries, Pratt and Whitney, Aerojet General, United States Government institutions----Frankford Arsenal, and NASA (Marshall Space Flight Center and Langley Research Center)----and foreign governments, such as Great Britain, France and Japan.

The actual explosive welding process is accomplished by a collision of two metal plates explosively driven together. The basic mechanism of the metallurgical bonding/jetting process has not been exactly determined. To quote from the generally accepted theory, Reference 1, "A jetting collision is defined as an oblique collision in which the plate velocity, pressure, collision angle and collision point velocity are controlled such that a jet or spray of metal is formed at the apex of the collision and is forced outward from between the colliding plates at very high velocities. A jet is pictured in the oblique

collision shown in Figure 1." The explosive welding process strips off both surfaces due to the collision of the plates, and the high pressures produced by the impact forces the now clean surfaces into intimate contact to achieve metallurgical, intermolecular bonding. The technique that is most closely analogous to this process is vacuum welding; two surfaces cleaned under a hard vacuum and pressed together mechanically can produce intermolecular bonding.

Explosive welding operations have generally been oriented toward area bonding, the cladding of metals. Relatively large quantities of "bulk" explosives, such as TNT (trinitrotulene), nitroguanidine and dynamite are hand-spread over the area to be welded. It is then initiated along one edge, and the detonation front sweeps across the area. A prerequisite for stable explosive welding is that the velocity of the collision point be less than the metal's sonic velocity.

Difficulty has been experienced by investigators in the explosive welding field in producing long, continuous seam welds in small area bonds, such as below one-half inch in width. Reference 2 describes a technique utilizing "primacord", a commercial name given to a cylindrically shaped, fabric-wrapped explosive cord. This joining technique relies on shaping at least one of the materials to be joined into a non-coplanar setup to achieve a joint that has a "width to length ratio of at least 1:10 or greater." Also, a caution is given that the detonation velocity of the primacord should not exceed 120% of the higher sonic velocity of the metal to be joined. As noted in Reference 2, "When the detonation velocity does exceed this amount, oblique shock waves often ensue that prevent formation of a strong metal-to-metal bond between the metal layers."

This report describes a novel small-scale explosive seam welding technique (small explosive quantities and plate thicknesses) developed and demonstrated in lengths to twelve feet at NASA Langley Research Center; the preliminary work is described in Reference 3. The joining mechanisms of this welding concept are shown in Figure 2 in the sketches. The plates to be welded are first separated and placed in parallel. The ribbon explosive which was developed for this technique is then placed on the plate to be welded and initiated. The explosive pressure drives the top plate downward, causing it to bend so that the center of the area under the explosive is the first to contact the lower plate. As the plate continues its descent, symmetrical critical oblique collision angles, producing the required jetting actions, are established to the sides. No joining occurs in the center area of initial plate contact. Jetting cannot be established in the direction of detonation, since the explosives' detonation velocity is about 150% of the sonic velocity in most metals. The actual jetting vectors produced are at  $60^{\circ}$  to  $75^{\circ}$  from the direction of detonation propagation. The photograph in Figure 2 shows the jetting streaks and bond area (the buffed-appearing area) produced in an explosive weld in aluminum.

This explosive welding technique was demonstrated by joining 0.040 to 0.125 inch thick aluminum to similar thicknesses or to 0.25 inch thicknesses in a variety of aluminum alloys and combinations of alloys tempered to maximum hardness and strength. Also, titanium was joined in a thickness of 0.056 inch. Four lap-type joints were constructed with these materials, producing strengths up to that of the parent metal. The joints were examined photomicrographically,

and tested for pressure sealing capability. The effect of vacuum on the welding process was investigated. Some structures were constructed that represent potential fabrication applications.

#### APPARATUS

The ribbon explosive developed under this study is shown in cross section in Table 1. The explosive, RDX (cyclotrimethylenetrinitramine) is encased in a lead sheath that has been shaped into a thin rectangular cross section. The explosive quantity is commonly designated in grains/running foot of length. The detonation propagation velocity of this explosive is 26,000 feet/second. A localized pressure of several million psi is achieved in less than one microsecond, and has a duration of less than five microseconds. The flexibility of the explosive, due to its lead sheath, allows it to conform to as little as a 0.125 inch radius. This explosive ribbon is manufactured to aerospace standards with less than ten percent variations in explosive quantity down its length. The cost for manufacture of the material for this study was about one dollar per running foot in quantities of several thousand feet, plus shipping costs.

Commercial blasting caps, Dupont Model E-106, containing approximately two grains of high explosive, were used in this study to initiate the ribbon explosive.

Very little tooling is required to accomplish this welding technique: masking tape, aluminum shims to separate the plates, aluminum bars for anvils, and "C" -clamps to hold the anvils in place during the welding operation.

#### PROCEDURE

The approach for this study was divided into three major phases: optimize the major explosive welding variables, develop explosively welded joints, and conduct analyses and demonstrations for potential fabrication applications.

Explosive Welding Variables--The following ten major variables were studied to determine and optimize their influence in explosive welding:

- |                                |                            |
|--------------------------------|----------------------------|
| 1. plate materials             | 6. plate deformation       |
| 2. plate thickness             | 7. mechanical shock        |
| 3. explosive quantity          | 8. metal grain orientation |
| 4. standoff (plate separation) | 9. weld length             |
| 5. plate surface               | 10. explosive residue      |

1. Plate materials---A variety of aluminum alloys, exhibiting a wide range of hardness and malleability, were studied: 2024, 2024 ALCLAD (1200 series clad), 2219, 6061, and 7075. Titanium, Ti-6Al-4V, was welded in the fully annealed condition. As received mill stock was used in all tests.

2. Plate thickness---Plate thicknesses from 0.040 to 0.125 inch were studied; the most influential performance factor in plate thickness is the required bending of the plate during the welding mechanism.

3. Explosive quantity---The objective in this area was to optimize the explosive quantity to maximize the bond area, but minimize the damage to plates.

Also, a minimum quantity of explosive would decrease the mechanical shock in the plates during the welding operation and the sound and fragment shielding requirements.

4. Standoff (plate separation)---Plate separation distance and separation techniques were investigated. Separation distances were varied from zero to 0.125 inch. A variety of separation techniques, shown in Figure 3, were evaluated. Techniques "a" through "d" used a 0.063-inch 2024-T3 ALCLAD plate welded to a 0.25-inch 6061-T6 base plate for comparison. Techniques "e" and "f" used pre-bent plates of titanium, Ti-6Al-4V, of equal thickness with the ribbon explosive placed on both sides of the plate combination.

5. Plate surface---The effects of surface oxides, cleanliness, and smoothness were evaluated. Due to the markedly different hardness/malleability properties of oxides and the difficulty in determining oxide thicknesses, all aluminum and titanium alloy samples were chemically cleaned. This cleaning also removed oils and other surface contamination. Observations were made on the effects of surface scratches on weld performance.

6. Plate deformation---Techniques were investigated to minimize the undesirable indentations in the plates produced immediately beneath the ribbon explosive during the welding operation. Figure 4 shows the experimental setup using 0.063 to 0.125 inch 2024-T3 ALCLAD plates. The following "buffer" materials were placed between the ribbon explosive and the 0.063-inch plate: three layers (approximately 0.015 inch) of masking tape, 0.015 inch layer of epoxy (Ecco Bond) a 0.040-inch 2024-T3 ALCLAD plate, and a 0.040-inch 2024-T3 ALCLAD plate epoxied with a 0.010-inch thickness to the 0.063-inch plate.

7. Mechanical shock---An analysis and tests were made to determine and limit the effects of internal pressure shock waves created in the metal plates by the explosive pressure and the impacting of the plates during the welding operation.

8. Metal grain orientation---To determine the effect of the metals' internal grain orientation on the explosive welding operation, or the strength of the welded joint, welds were made across and with the grain.

9. Weld length---The shortest possible weld lengths were determined by observation of welds at their starting and ending points. To determine long-length limitations a 12-foot weld was made in 0.063 to 0.25 inch 2024-T3 ALCLAD. Thirty one-inch samples were made down its length to determine the uniformity of the joint.

10. Explosive residue---The explosive residue (materials, quantities, and location) was observed during and after the welding operation.

Weld Joint Development---Several explosively welded joints were developed that are representative of current fabricational materials and requirements. Materials were selected for their strength in the most useful conditions of maximum hardness and temper. An effort was made to maximize the simplicity of the welding operation in terms of material preparation, weld setup, and necessary tooling.

Each joint was fabricated in a 12-inch length, using the optimum set of variables developed for each particular material or combination of materials. The joints were evaluated by cutting them into 1-inch-wide samples which were pull-tested along the plate axes. No effort was made to provide jigs or fixtures which could place the joint in absolute shear during evaluation. The ultimate strength of each sample was recorded and compared to the tensile strength of the plates in pounds per running inch.

Applicational Analyses---To evaluate potential applications of this joining technique, several investigations were conducted: 1. Photomicrographs of joint interfaces, 2. pressure integrity of joints, 3. the effect of vacuum on the welding operation, 4. explosive contamination and safety, and 5. fabrication of some useful structures.

1. Photomicrographs---To evaluate and predict more fully the properties of explosively welded joints, representative joint samples were examined photomicrographically.

2. Pressure Integrity Tests---To determine if this weld joint was airtight, 0.040 and 0.063 by 3 by 3 inches 2024-T3 ALCLAD plates were welded to 0.5 by 3 by 3 inches 6061-0 plates, as shown in Figure 5, and pressurized with dry nitrogen.

3. Vacuum Effects---The effect of vacuum on the explosive welding operation was evaluated by comparing the performance of two similar joints: one welded in the atmosphere, and the other welded in a vacuum of  $1 \times 10^{-5}$  torr (a simulated altitude of approximately 400,000 feet).

4. Explosive Contamination and Safety---An effort was made to observe the effects of explosively created products on contamination to localized areas, and the requirements for shielding for personnel, as well as the safety requirements for personnel in handling and initiating the explosive.

A technique was developed to confine all explosive products, shown in cross section in Figure 6. The explosive is placed in a 3/47 stainless-steel tube. Properly designed end fittings provide total confinement. To demonstrate the performance of this technique, several tests were conducted by welding 0.040 to 0.25 inch 2024-T3 ALCLAD plates as follows:

1. An unconfined length of 15 grains/foot explosive was compared to the same 15 grains/foot in a totally sealed tube, 2. a 20 grains/foot length inside a tube with no end fittings was compared to the same 20 grains in a totally sealed tube, and 3. a length of 25 grains/foot explosive in a tube with no end fittings was used to weld 0.063 to 0.25 inch 2024-T3 ALCLAD plates.

5. Structural Fabrication Demonstrations---Several potentially useful structures were fabricated in this study: 1. A half-inch plug was welded into a 1-inch-diameter tube using a setup shown in Figure 7. The assembly was pressure-checked and pull-tested through the plugs along the tube axis. 2. A 0.056-inch-thick (1 by 1 inch) titanium rib was welded to a flat plate, as shown in Figure 8. The strength of the joint was determined by comparison

to standoff technique "f" in Figure 3. 3. A 1/12-scale model of a space station-type structure was constructed (see Ref. 3), measuring 18 inches high and 18 inches in diameter. The 0.040-inch 2024-T3 ALCLAD skin, bulkheads, and deck were welded to 6061-0 0.25 by 0.5 by 18-inch-diameter rings and 0.125 thick, 0.75 by 0.75 by 18-inch angle. Two 2-inch-diameter plexiglass portholes were installed between the skin and 0.125-inch 6061-0 plates.

## RESULTS

The results for this study will be presented in the three major phases previously outlined: Optimize the major explosive welding variables, develop explosively welded joints, and conduct analyses for potential fabrication applications.

Explosive Welding Variables---These variables at first appear to be independent, but during the welding operation actually become dependent. Due to the rapidity and violence of this operation, it is often difficult to determine which variable, or variables, predominated in producing success or failure.

1. Plate Materials---The hardness and malleability of the materials affect its bending in producing the weld mechanisms; in general, the high-strength alloys require considerably more explosive energy. The harder materials create and efficiently transfer high-pressure shock levels, which are detrimental to the welding operation.

2. Plate Thickness---As the plate thickness increases, the explosive quantity must be increased, nonlinearly, to achieve the welding mechanism. Due to the pressure shock waves created during the welding operation, heavier plates produce beneficial attenuations and delay shock-wave reflections from influencing the weld operation.

3. Explosive Quantity---The optimum explosive quantities used to maximize joint strength and minimize plate damage are listed in tables described in the weld-joint development section.

4. Standoff---Plate separation distance prior to explosive welding does affect joining performance. A finite distance is required to allow the plates to be accelerated to the high velocities required to achieve welding. Again, this response is associated with another variable - thickness and mass of the plates. In the joints created in this study using 0.040 to 0.125-inch-thick materials, standoff distances were set from 0.010 to 0.040 inch. Standoff distances to 0.125 inch were evaluated but unless these distances are held to less than half the plate thickness or fully annealed materials are used, fracturing and shearing can be expected.

The results of the standoff comparison test series, which used the setup shown in Figure 3, are tabulated below. The parent metal strength of the 0-063-inch plate in techniques "a" and "d" was 4300 pounds/running inch, and for the 0.056 titanium "e" and "f," 7320 pounds/running inch.

Technique	Average strength, pounds/inch	Std. dev.
a	3410	640
b	3870	1000
c	4300	450
d	4010	430
e	7320	110
f	5550	1540

The standoff in technique "a" can be accomplished with any convenient material; this study utilized both masking tape and aluminum shims. Standoff "b" allows the plates to be in full contact, simplifying the required setup. The scattered performance in technique "b" was partially caused by difficulty in bending the metal into the narrow groove while producing the welding mechanisms. Some mechanical locking was achieved at the groove's edge in both techniques "b" and "c." However, in "c" and "d" no plate bending was required to initiate the weld mechanism. The critical jetting angle is already present and jetting is immediately established. Both techniques "c" and "d" produced a central unbonded area that was approximately 0.030 inch, the width of the peak of the inverted "V."

Since the parallel plate process, standoff technique "a," was not effective in the welding of titanium, techniques "e" and "f" were developed. In both techniques, the plates were initially separated to allow for the development of high impact velocities. On impact the critical collision angle is already established, producing the required jetting mechanism. Except for the first and last one-half inch of the joint welded in technique "e" the joint had a higher strength than did the parent metal; all the samples failed in the parent metal of the coupon, one-half inch away from the joint. The joint in technique "f," however, lacked both the high strength and uniformity.

5. Plate Surface---The effects of surface oxides on aluminum and titanium alloys were not evaluated due to the difficulty of determining the amount and type of oxides. However, no substantial change in joint performance was noted in specimens chemically cleaned and held at laboratory ambient for 4 weeks. Only aluminum alloys had sensitivities to oxides; commercially pure aluminum (1100, 1200, and the ALCLAD series) required no oxide removal. Also, surface contamination such as oils and lubricants inhibited welding operations. Again, the degree of contamination is difficult to evaluate. This aspect is beneficial in preventing welding in selective regions, such as spot-welding. Narrow surface scratches deeper than 0.003 inch prevented joining in that particular area. However, the jetting mechanism was apparently unaffected continuing in the area surrounding the scratch.

6. Plate Deformation---The results of the "buffer" tests (Fig. 4) to limit the detrimental explosive pressure-induced indentations are shown below. The 0.063-inch material has a strength of 4300 pounds/inch.

Buffer material	Thickness, inch	Joint strength, pounds/inch	Std. dev., pounds
Masking tape	0.015	3800	320
Epoxy (Ecco Bond)	0.015	3980	300
2024-T3 ALCLAD	0.040	3767	510
2024-T3 ALCLAD Epoxy (Ecco Bond)	0.040	4200	400

The masking tape buffer alone increased the indent radius to 0.030 inch, and the epoxied plate increased it to 0.125 inch. A second benefit in using buffers is the diffusing of the explosive pressure, producing larger area, higher strength bonds. The inefficiency of the single-plate buffer is caused by pressure-reflective losses at the plate interface. A third benefit of buffers is the protection of plate surfaces from explosive contamination. The masking tape leaves only an imprint of the tape's texture after the firing.

7. Mechanical Shock---High-pressure shock waves are generated in the metal plates during the explosive welding process in several ways. Figure 9 shows the shock waves created when one plate is explosively driven against a second plate. The explosive pressure first induces a pressure to accelerate the plate, followed by a second shock produced when the plates impact. The magnitude of these shock waves is significantly increased by the hardness and lack of malleability of the materials. The shock waves created on impact propagate through the top and the base plates, and are reflected from outer surfaces. If these plates are of the same thickness and material and have the same sonic velocity, the reflected shock waves will arrive simultaneously. The rarefaction wave which is 90° out of phase with the compression wave, then places the weld in tension, causing the joint to fail. The resultant shock-wave vectors of each plate are reflected from the ends of the plates, compounding the destructive influence.

A final shock wave problem is the influence on structure or systems in the immediate vicinity of continued explosive welding operations. The shock waves can propagate through structure (attenuated by material, distance, and mechanical interfaces) and destroy already established welds or delicate components attached to the structure.

The "end effect," which can cause destruction of the entire joint, can be minimized by not welding the whole length of the joint -- stopping the welding about 1 inch from the end. All reflected shock waves can be reduced by adding "anvils" of the same materials that are being welded. An example of one technique is shown in Figure 10. This added mass reflects less of the shock waves into the plates, as described in Reference 1. Further aids in absorbing and dissipating shock waves are provided by metal shims to accomplish plate standoff and silicone grease which responds like an incompressible fluid under dynamic loading.

Although shock-absorbing anvils are always beneficial, not all materials and setups require them to achieve success. Such was the case of aluminum

alloys in the fully annealed condition, the ALCLAD series, and the joining of thin plates to heavy plates (6061-T6 was demonstrated to have this ability). However, anvils were necessary in joining thin-to-thick setups of 2024-T4, 7075-T6, and 2219-T31 to 6061-T6. Also, anvils were required in welding equal thickness plates of 6061-T6, 2219-T31, and Ti-6Al-4V. So much shock energy was created in the weld attempts with 2024-T4 and 7075-T6 to like materials, anvils could not prevent the destruction of the joint immediately after it was established.

8. Metal Grain Orientation---The grain orientation of the metal had an appreciable effect on the materials ability to be bent to establish explosive welding. The metal plates respond in a near-fluid manner to the several million psi explosive loading; this allows the plates to be bent as much as its own thickness when worked across the grain. However, a bend of only half the plate thickness could be tolerated when worked with the grain, due to shearing along grain boundaries. Once welded with minimal bending, no appreciable change in joint strength was noted due to grain orientation.

9. Weld Length---The smallest weld length must be controlled by the individual materials efficiency in initiating the welding mechanisms: the finite distance required to achieve stable welding. For aluminum, this length is approximately 0.25 inch, and for titanium, 0.5 inch. A second length-limiting factor is the end effects mentioned in the section under mechanical shock, producing weakened joints in the last 0.5 inch. To achieve the strongest possible properties for any selected bond length, the welding operation would have to be initiated before, and carried beyond, the desired bond area.

In determining the long-length ability of this explosive welding mechanism, a 12-foot weld was made in 0.063 to 0.25-inch aluminum. The average strength of the 30 one-inch samples was 2660 pounds per running inch, with a standard deviation of 320. No indication of changes in the explosive welding mechanism was observed down the entire length.

10. Explosive Residue---The residue that is produced on functioning of the ribbon explosive in a weld setup consists of particles of lead (broken and melted into small particles), dustlike particles of unreacted carbon (the smoke produced), and the masking tape that was used to hold the explosive in place. Due to the explosive dynamics, this residue can be driven between the plates before they impact in the welding operation, causing surface contamination and low-strength joints. To inhibit this movement of residue, the access areas to plate interfaces are taped over. Also, the residue is prevented from contaminating plates by using buffer materials, as described in the section on plate deformation.

Weld Joint Development---The four explosively welded joints that were developed and demonstrated in this study are shown in Figure 11. The operational setups and mechanics follow:

1. Dissimilar-Thickness Lap Joint---The plates are separated in a parallel configuration. The ribbon explosive is placed over the desired weld area and initiated.

2. Similar-Thickness Lap Joint---The plates are separated in a parallel configuration. The ribbon explosive is placed on both sides of the pair, directly opposite each other, and initiated simultaneously (one blasting cap). The forces created by the explosive are exactly canceled.

3. Sandwiched-Butt Joint---The two plates sandwiching the main structural plate are separated in parallel. The ribbon explosive is placed on both sides of the sandwich, directly opposing, and initiated simultaneously (one blasting cap). Each joint pair was accomplished separately.

4. Scarf Joint---The plates are separated in parallel. The ribbon explosive is placed on both sides of the pair, but the ribbon explosives' longitudinal axes are displaced relative to each other by one-half the width of the explosive. On simultaneous initiation the explosive pressure produced is not equally opposed over half its area, causing both the horizontal axes of the plates to bend into alinement, and the welding of the plates.

The detailed results of the four explosively welded joints are compiled in Tables 2 through 5, showing the materials welded, the explosive quantity used, the thin-plate material strength, and the average strength and standard deviation of each 10-sample group.

1. Dissimilar-Thickness Lap Joint, Table 2---The excellent malleability properties of 6061-T6 permitted the formation of many different alloy combinations; many of these combinations produced bond areas in the joint that could support the strength of the parent material. The lower strengths of some combinations can be attributed to the welding inefficiency (note the larger standard deviations) caused by both lower strength and malleability of the 0.25-inch materials. The joint strength is controlled by the weaker material. Noteworthy exceptions of the low-strength 0.25-inch materials are 2024-T3 ALCLAD and 6061-0. The high malleability of these materials appreciably increased the effective bond areas of the joint.

All of the possible combinations were not attempted. However, any combination using a 0.25-inch 7075-T6 or 2024-T4 base plate failed to join, again due to the hardness and low malleability.

2. Similar-Thickness Lap Joint, Table 3---The strength of the 2024-T3 ALCLAD joints again are limited by the soft commercially pure cladding material. However, a large percentage of the samples of the 6061-T6 and 2219-T31 joints exhibited strengths superior to the forces required to break the joint. These samples broke in the metal adjacent to the welded area. Since these joints were not placed in shear, but allowed a bending moment that was the thickness of the plate, plus the standoff distance, breakage at the weld edge was predictable.

The titanium joint exhibited markedly different characteristics. Due to the angular standoff setup, technique "e" of Figure 3, and the high degree of local rigidity of this material, the axes of the plates were driven into nearly perfect alinement and only minimal localized bending occurred. This combination of attributes produced a joint that exceeded the properties of the

parent metal. The weld samples failed in the plate at a distance of about one-half inch from the joint. The first and last half-inch of this joint exhibited approximately half the strength of the remaining samples, and were not included in the average strength calculation in Table 3. The causes of these weaknesses are explained in the Explosive Welding Variables results under the section on weld length.

3. Sandwiched-Butt Joint, Table 4---The 6061-T6 joints exhibited nearly parent metal strengths. It was not possible to predict which joint or member would fail. Considerable difficulty was encountered in the titanium joint, primarily due to alinement. Any misalinement caused an uneven distribution of the load within the members and a resultant failure in only one member.

4. Scarf Joint, Table 5---This welding technique produces highly efficient, high-strength joints primarily through two attributes: a larger bond area than that created in a straight lap joint, and part of this bond area is placed in tension. Also, the bending at the joint to produce plate alinement, a radius of approximately 0.25 inch, is accomplished without appreciable metal fracturing. This technique is so efficient that the joint of 0.040 inch 2024-T3 ALCLAD exhibited parent metal strength, despite the fact that the actual bond is achieved only in the soft cladding material.

In comparison to the similar-thickness lap joint, the 2024-T3 ALCLAD performance was considerably improved: for the 0.063-inch-thickness, the lap joint had an average strength of 2670 pounds/inch, and for the scarf, 3920 pounds/inch; for the 0.090 thickness, the lap was 3500 pounds/inch, and for the scarf, 5290 pounds/inch.

The 6061-T6 material did not respond as well in the heavier thicknesses to this joining technique. The 0.090-inch joint had a decrease in strength, as compared to the lap joint; the lap joint's strength was 4330 pounds/inch, and the scarf, 3830 pounds/inch. The 0.125-inch-thickness failed both to bend into alinement or bond.

#### APPLICATION ANALYSES

The results of the investigations in this area will be detailed in five divisions: photomicrographs, pressure integrity tests, vacuum effects, explosive contamination and safety, and structural fabrication demonstrations.

1. Photomicrographs---A representative example of a complete cross section of an explosive joint is shown in Figure 12, which was divided into four sections to permit printing on a single page. The joint is 0.063-inch 7075-T6 bonded to 0.250-inch 6061-T6. The central unbonded area, approximately 0.2 inch in length, is flanked by two symmetrical 0.050-inch bond areas. This ratio of bonded to unbonded areas is not necessarily representative of all weld joints. This ratio is affected by many explosive welding variables such as material, thickness, explosive quantity, and standoff technique. The largest gap in the central area is approximately 0.001 inch. The bond areas exhibit the classical "wavy" interface of all explosive welding.

The unbonded area, which runs the longitudinal length of the weld represents a possible chemical path for corrosion. However, properly selected weld patterns could seal it.

Since no material is added in this joining process, sharp notches are created at the joint interfaces. This could be a potential stress point for fatigue failure. Tiny internal fractures have been observed in heavier plates in the areas of maximum deformation caused by explosive pressure (the joint edges), again producing stress concentrations. However, as described in the section on plate deformation, this damaging effect can be reduced by the proper selection of buffer materials.

A series of photomicrographs of dissimilar-thickness lap joints are shown in Figure 14. The higher magnifications show the "wavy" interfaces. The peak-to-peak dimensions of these waves are in no case larger than 0.002 inch, showing that this bonding technique is only "skin deep." The parent metal grain structure near the bond areas is virtually unaffected.

The 0.063-inch 2024-T3 ALCLAD to 0.250-inch 6061-T6 joint shows that the 1200 series cladding is essentially undamaged, following the contours of the plate, immediately below the explosive and in the bond area. The "inverted V" standoff technique produced a nearly complete bond across the interface, reducing the unbonded area to only the peak of the "V." The pronounced wavy interface associated with the parallel plate setups is nearly absent.

A series of photomicrographs of similar-thickness joints are shown in Figure 14. The bond area of the 6061-T6 joint required severe etching to differentiate between the two plates. The titanium joint has a large central unbonded area, but the bond itself is excellent. The same bond under higher magnification shows a 0.001-inch peak-to-peak wavy interface, but emanating from these peaks are rays of apparent crystal reorientations, exhibiting peak-to-peak dimensions of 0.0045 inch.

These photomicrographs reveal that each interface is unique to materials and physical setup; so unique that each configuration can be identified by the "signature" of its explosively welded interface. There are no fusion or diffusion zones in these bonds, only grain boundary-width lines separating one metal from another.

2. Pressure Integrity Tests---After welding the plates in the configuration shown in Figure 5, the assembly was pressurized with dry nitrogen to 1000 psi and held for 5 minutes with no appreciable leakage. The 0.040-inch plate burst at 1300 psi, and the 0.063-inch plate burst at 1900 psi. The complete weld did not fail; the rupture occurred in the plate, breaking through the middle of the bond area.

3. Vacuum Effects---No appreciable change in strength was observed in the fabrication of a 0.090-inch 2024-T3 ALCLAD scarf joint under vacuum. A joint strength fabricated under atmosphere had an average of 5290 pounds/inch with a standard deviation of 510; a second joint fabricated under vacuum had a strength of 5420 pounds/inch with a standard deviation of 490. Air is simply a compressible fluid between the plates to be welded, resisting their movement

during the welding operation. However, air is beneficial in inhibiting the movement of explosive residue, helping to prevent contamination of areas to be welded, prior to the actual welding mechanism.

4. Explosive Contamination and Safety---The explosive residue, fragments of lead, carbon, and tape, as described in item 10 of the explosive welding variables, can damage and contaminate surrounding surfaces and are potentially hazardous to personnel. The bulk of this residue is emitted within  $\pm 10^\circ$  of a plane on the center line of the explosive and perpendicular to the plate; no explosively driven residue is deposited on the plate surface, only the fallout from the surrounding volume.

Due to the very small explosive quantities used by this technique, only minimal shielding is necessary to capture or redirect this residue. A 0.040-inch aluminum structure placed 18 inches from the explosive source will stop these fragments. The very high pressure created by these minute amounts of explosive dissipates rapidly with distance; at 18 inches, the actual pressures are estimated to be less than one psi.

A second potential hazard to personnel is the explosive sound. The sound created by the ribbon explosive at 10 feet is comparable to the sound produced by a shotgun at 1 foot from its muzzle. This sound can be effectively muffled by using separate welding rooms, properly equipped with acoustical materials.

All explosive products, including lead, smoke, and sound can be totally confined by the apparatus shown in Figure 6. The only observable effects are the expansion of the tube and the rattling of metal. The ribbon explosive is placed in the bottom of the tube adjacent to the plate to be welded. On initiation, the explosive pressure transfers through the tube and accelerates the plate to be welded producing the normal explosive welding operation. The pressure transfer is facilitated by the use of silicone grease, which acts like an incompressible fluid under dynamic loading, at the tube-to-plate interface. The silicone rubber attenuates and diffuses the explosive pressure, preventing tube rupture. Flexible end fittings must be provided to achieve total confinement.

In determining the performance of this confinement technique, welds were made in 0.040-inch to 0.25-inch aluminum. The performance of a joint created with 15 grains/foot ribbon explosive directly applied to the plate (no tube) was 2300 pounds/inch with a standard deviation of 200; 15 grains/foot in a totally confined tube produced a weld of 1780 pounds/inch with a standard deviation of 240, a strength loss of 23%. A joint created by a 20 grains/foot ribbon explosive in an open-ended tube had a strength of 2300 pounds/inch with a standard deviation of 230; a totally confined 20 grains/foot ribbon explosive produced a joint strength of 2300 pounds/inch with a standard deviation of 240, no appreciable change.

To evaluate the maximum confinement ability of the tube, a 25 grains/foot ribbon was tested in an open-ended tube on 0.063 to 0.25-inch aluminum plates. The tube did not rupture and produced a joint with a strength of 2900 pounds/inch with a standard deviation of 170.

This explosive material, RDX, is not sensitive to inadvertent initiation during handling, cutting, or setup. Deliberate attempts would have to be made to expose the explosive itself and impact it sharply between hard surfaces to initiate it. The possibility of initiating the explosive inside its sheathing by deliberate hammering is remote. The ribbon explosive may be cut with sharp instruments, such as scissors, knives, or razor blades. However, the explosive is sensitive to heat; it will sublime slowly at approximately 200° F and burn at approximately 300° F. This burning is not detonation and the several million psi pressure is not generated. This material has not been tested to determine the unlikely possibility of the burning being accelerated to detonation.

Explosive materials such as HNS (hexanitrostilbene) and Dipam (dipicramide) are available that are completely insensitive to any shock stimulus other than that delivered by another explosive. Also, these materials can withstand 500° F for at least 5 minutes without burning.

The inexpensive electrically initiated blasting cap used to initiate the ribbon explosive is the major potential hazard in this operation. Special care must be taken in its handling to prevent impacts and static electricity, or the application of stray energy through the firing leads. Proper handling by personnel and adequate electrical grounding and firing systems can virtually eliminate this problem.

5. Structural Fabrication Demonstrations---To demonstrate the potential of this welding technique, several structures were fabricated and evaluated: an aluminum plug was welded into an aluminum tube, a titanium rib was welded to a flat titanium plate, and a 1/12 aluminum scale model of a space station-type structure was constructed.

Two plugs were welded into the tube, as shown in Figure 7. The assembly was pressurized with dry nitrogen to 1500 psi through a fitting mounted in one plug with no appreciable leakage. A pull-test on the aluminum plugs produced a tube failure at 8300 pounds force which is equivalent to a 38,100 psi tensile load. The weld joint was not pulled off either plug.

The titanium rib, fabricated in the setup shown in Figure 8, is shown in Figure 15. The first, and last inch of these joints failed to weld. This result was supported by similar tests conducted in Figure 3, technique "f." The average strength of this joint was 5550 with a standard deviation of 1540. This joint appears to be extremely sensitive to setup variables of explosive locations and standoff uniformity.

The space station-type structure fabrication, joining 0.040-inch skin, bulkheads, and deck to 18-inch-diameter rings and 0.125-inch-thick 0.75-inch angle was highly successful. The average weld strength was approximately 1000 pounds/inch. See Figure 16.

## CONCLUSIONS

The general efforts in explosive welding since the 1950's have been directed toward relatively large-area bonding of metal combinations that are difficult to join by other techniques. Considerable difficulty has been experienced in the production of narrow, long-length weld joints with this area-bond technique. This report describes a novel small-scale explosive seam-welding technique developed and demonstrated at NASA-LRC, which overcomes these difficulties. This technique can join a variety of aluminum alloys (2024, 2024 ALCLAD, 2219, 6061, and 7075) and aluminum alloy combinations (2024, 2219, 2024 ALCLAD, and 7075 to 6061) to 0.125 inch thickness, and titanium (Ti-6Al-4V) to 0.056 inch in seam welds less than one-half an inch in width with no apparent long-length limitation. Aluminum welds to 12 feet have been demonstrated.

The evaluation and demonstration of this explosive welding technique was accomplished in three major phases: evaluation of welding variables, joint development, and applicational analyses.

Ten major explosive welding variables were studied to determine their effects on welding performance. They are plate materials, plate thicknesses, explosive quantity, standoff-plate separation, plate surface, plate deformation, mechanical shock, metal grain orientation, weld length, and explosive residue. Adequate limitations or controls were demonstrated for all the variables except mechanical shock induced by the explosive and plate impact.

Four different explosively welded joints were fabricated and demonstrated in a variety of aluminum alloys tempered to maximum strength in a range of thickness and titanium. These joints are: dissimilar-thickness lap, similar-thickness lap, sandwiched-butt and scarf. These joints exhibited strengths up to that of the parent metal.

A series of applicational analyses were conducted. Photomicrographs revealed the classical "skin-deep" wavy interface (less than 0.002 inch) with no fusion or diffusion zones of conventional explosive welding. Since no metal is added in this joining technique, sharp notches exist at the outer edges of the bonded area between the plates, which could produce possible stress concentrations. In pressure tests, the explosively welded joints were demonstrated to be airtight. Also, this explosive welding technique is slightly more efficient under vacuum conditions.

The handling, cutting, and installation of the ribbon explosive is no more hazardous than many machining and fabricating processes. Very little shielding is required for containment of explosive products, and sound protection can be provided by conducting welding operations in acoustically shielded rooms. Furthermore, a technique was developed and demonstrated that can contain all explosive products, including fragments and sound, during explosive welding.

Several potentially useful structures were fabricated. An aluminum plug was welded into a thin-walled aluminum tube, achieving 85% of the tube's ultimate strength. A thin-walled titanium rib was welded to a flat titanium

plate of the same thickness. A 1/12-scale model of a space station-type structure was fabricated, using thin aluminum welded to aluminum rings and angle.

Recognizing the highly complex requirements in today's fabrication field, this small-scale explosive seam-welding technique can complement existing fabrication techniques through many of the advantages of conventional explosive welding techniques, as well as its unique advantages. This technique can join metals and alloys that are difficult, if not impossible, to achieve with non-explosive approaches. It does not affect the temper/strength characteristics of these alloys. It can join thin materials to heavy stock, and is insensitive to vacuum. The unique advantages of this technique include the ability to produce narrow, long-length joints with a high degree of efficiency and low cost. Eight ounces of this explosive, excluding the lead sheathing, can produce a weld joint 140 feet long in 0.125-inch aluminum at a cost of \$131 in materials. The reproducibility of this technique is shown by the small standard deviations of the 41 weld joints in this study, averaging 10% of their respective mean values. This technique is very simple, requiring few tools and only minimal personnel skill and training. Finally, weld joints can be made in setups that produce no unbalanced reactionary forces.

#### REFERENCES

1. Carpenter, S. H.; and Wittman, R. H.: "The Theory and Application of Explosive Welding," The University of Denver.
2. Blank, G. F.; and Bothe, B. A.: United States Patent 3,543,388, "Controlled Area Explosive Bonding," issued December 1, 1970.
3. Bement, L. J.: "Welding of Aluminum With Linear Ribbon Explosives," Presented at the Seventh Symposium on Explosives and Pyrotechnics, Philadelphia, Pennsylvania, September 8-9, 1971.

TABLE 1

Cross-sectional Dimensions of Linear Ribbon RDX Explosive

Explosive Load grains/foot	Thickness inch	Width inch
7	0.020	0.220
10	0.020	0.300
15	0.025	0.315
20	0.030	0.365
25	0.035	0.370

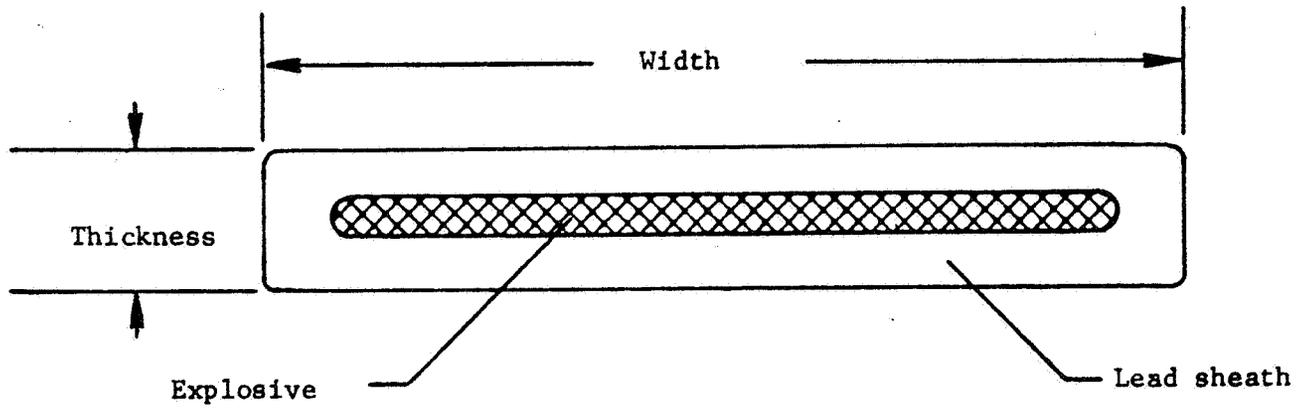


TABLE 2

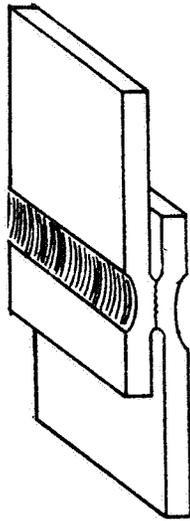
DISSIMILAR-THICKNESS LAP JOINT STRENGTHS



MATERIAL 0.063 to 0.250 INCH	EXP. QTY. GRAINS/FOOT	MAT. STRENGTH POUNDS/INCH	JOINT STRENGTH POUNDS/INCH	STD. DEV. POUNDS
6061-T6 to 2024-0	20	3000	2500	430
6061-T6 to 7075-0	20	3000	2600	430
6061-T6 to 6061-0	20	3000	3300	240
6061-T6 to 6061-T6	20	3000	3400	30
6061-T6 to 2024-T3A	20	3000	3000	200
2024-T3A to 2024-T3A	20	4300	2700	360
7075-T6 to 2024-T3A	20	5500	3400	200
7075-T6 to 6061-T6	20	5500	3400	830
0.070 to 0.250 Inch 2024-T4 to 6061-T6	20	4890	4380	830
0.100 to 0.250 Inch 2219-T31 to 6061-T6	25	6370	3120	740

TABLE 3

SIMILAR THICKNESS LAP JOINT STRENGTHS

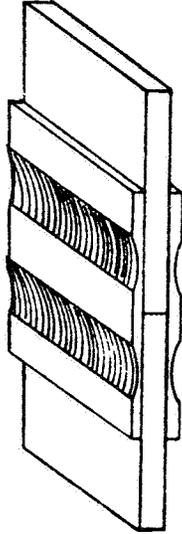


THICKNESS INCH	MATERIAL	EXP. QTY. GRAINS/FOOT	MAT. STRENGTH POUNDS/INCH	JOINT STRENGTH POUNDS/INCH	STD. DEV. POUNDS
0.063	2024-T3A	15	4300	2670	260
0.090	2024-T3A	20	6100	3500	220
0.125	2024-T3A	25	8600	3520	380
0.063	6061-T6	15	3000	2890	320
0.090	6061-T6	20	4300	4330	190
0.125	6061-T6	25	6000	4540	670
0.100	2219-T31	25	6370	5040	130
0.056	Ti-6Al-4V	25	7320	7320	112

CS  
CS  
CS  
A

TABLE 4

SANDWICHED-BUTT JOINT STRENGTHS

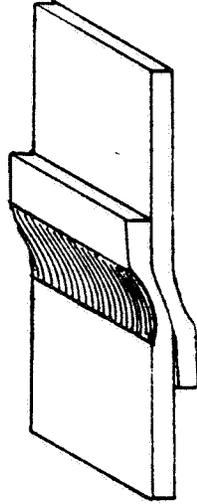


THICKNESS INCH	MATERIAL	EXP. QTY. GRAINS/FOOT	MAT. STRENGTH POUNDS/INCH	JOINT STRENGTH POUNDS/INCH	STD. DEV. POUNDS
0.040 to 0.063	6061-T6	15	3000	2880	310
0.063 to 0.090	6061-T6	25	4300	4100	580
0.063 to 0.125	6061-T6	20	6000	5720	720
0.025 to 0.056	Ti-6Al-4V	25	7300	6240	1140

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TABLE 5

SCARF JOINT STRENGTHS



THICKNESS INCH	MATERIAL	EXP. QTY. GRAINS/FOOT	MAT. STRENGTH POUNDS/INCH	JOINT STRENGTH POUNDS/INCH	STD. DEV. POUNDS
0.040	2024-T3A	7	2300	2490	100
0.063	2024-T3A	15	4300	3920	280
0.090	2024-T3A	20	6100	5290	510
0.125	2024-T3A	25	8600	4410	170
0.063	6061-T6	15	3000	2880	110
0.090	6061-T6	20	4300	3830	400

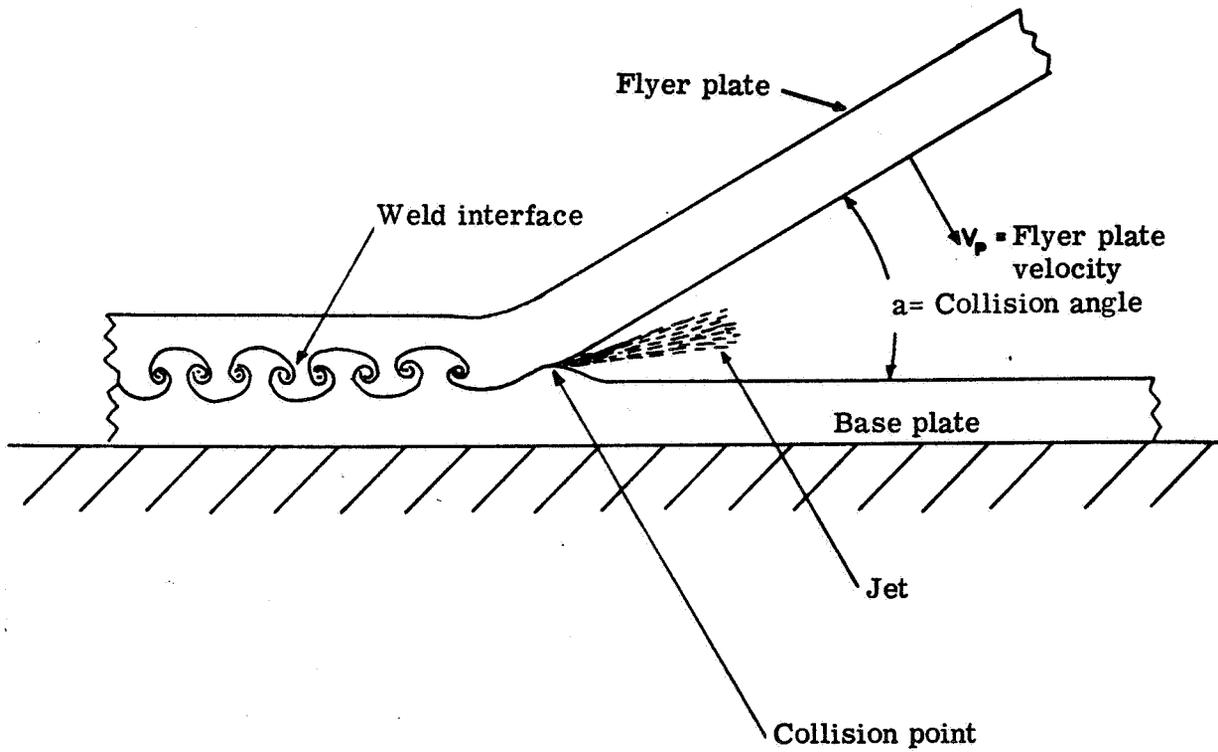
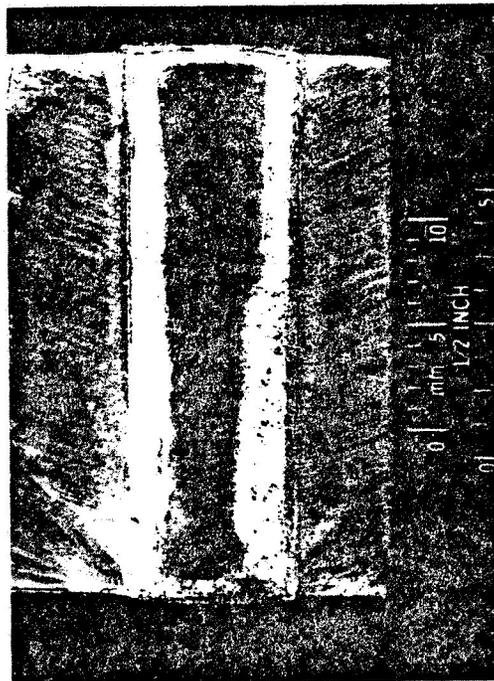
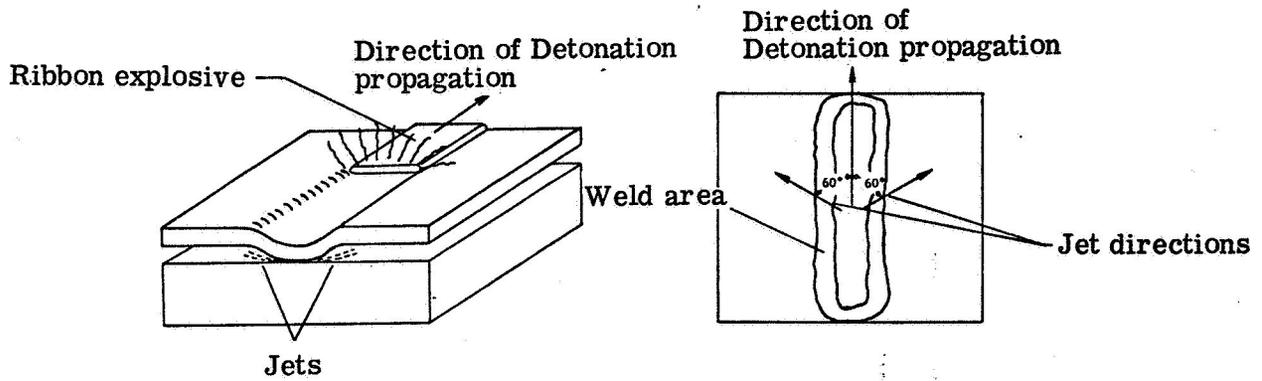


Figure 1. - Oblique collision of metal plates in an explosion welding operation.



Photograph of actual explosive weld, showing streaks produced by jetting action.

Figure 2. - Mechanisms of NASA-LRC explosive welding



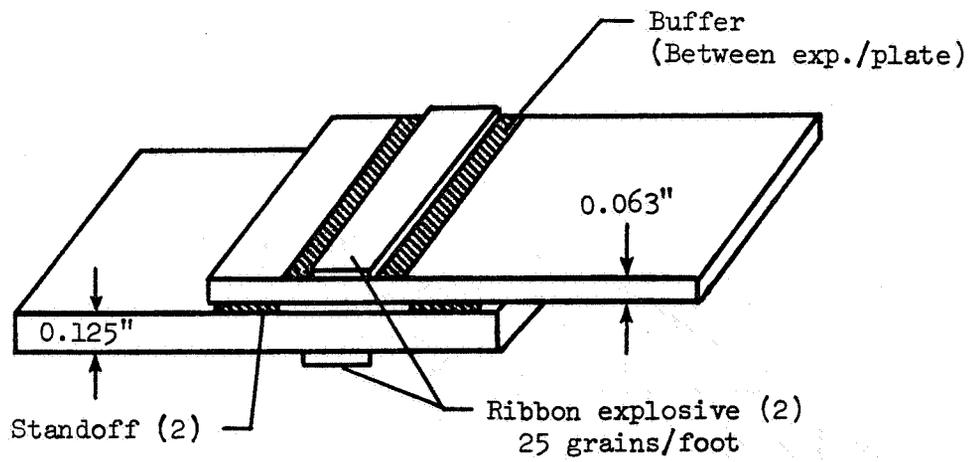


Figure 4.- Setup for buffer material evaluation.

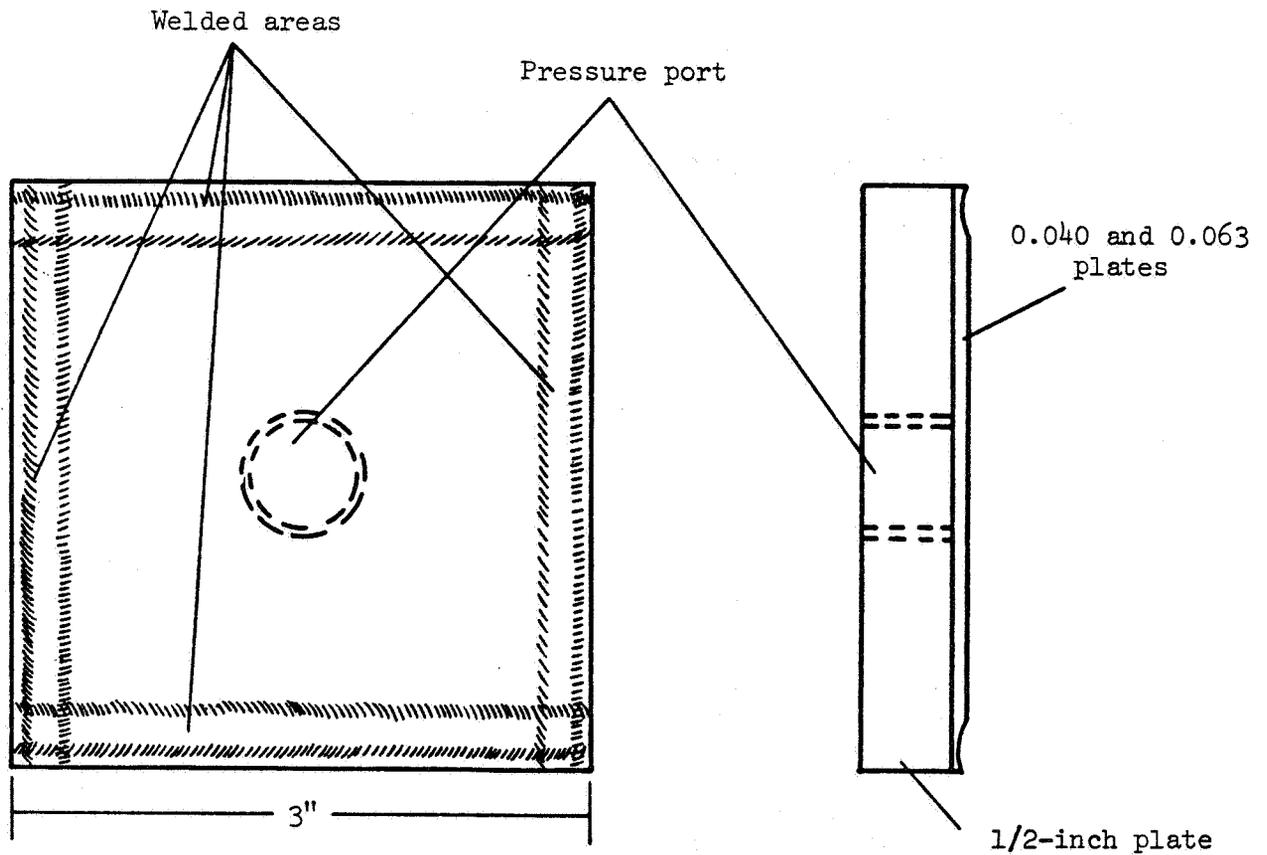


Figure 5.- Setup for pressure integrity tests.

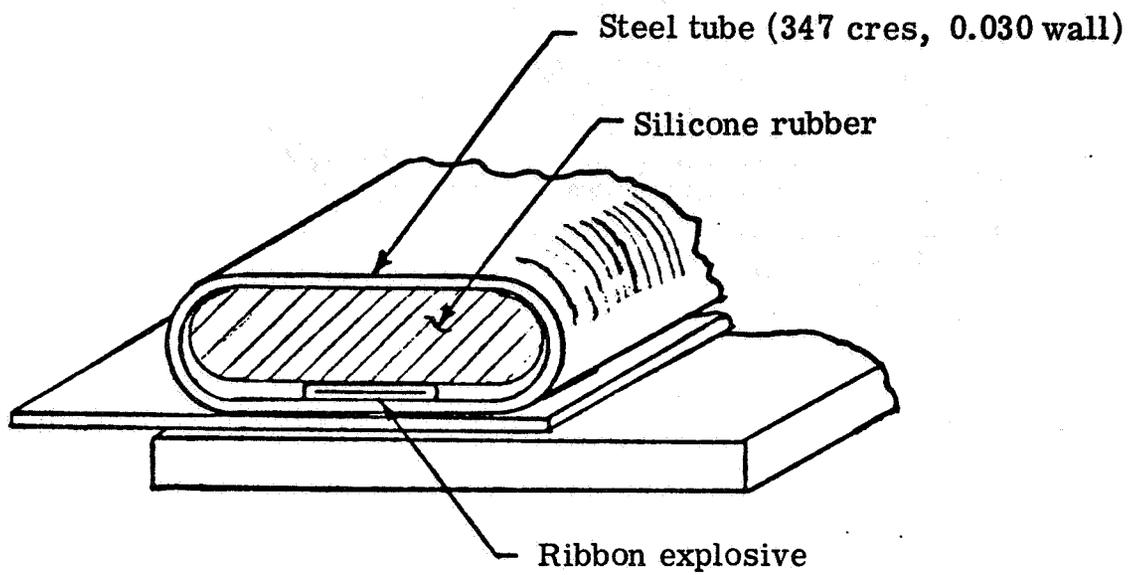


Figure 6. - Setup for explosive weld to achieve confinement of explosive detonation products.

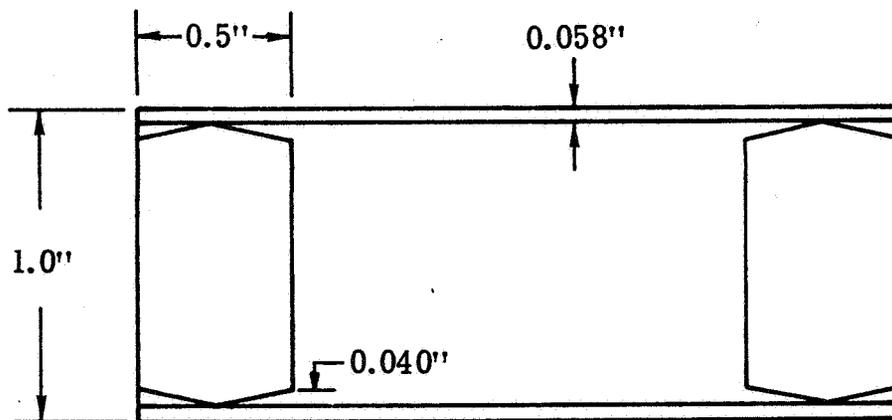


Figure 7. - Setup for explosive welding of 1/2" 6061-T6 plug in 1" 6061-T6 tube

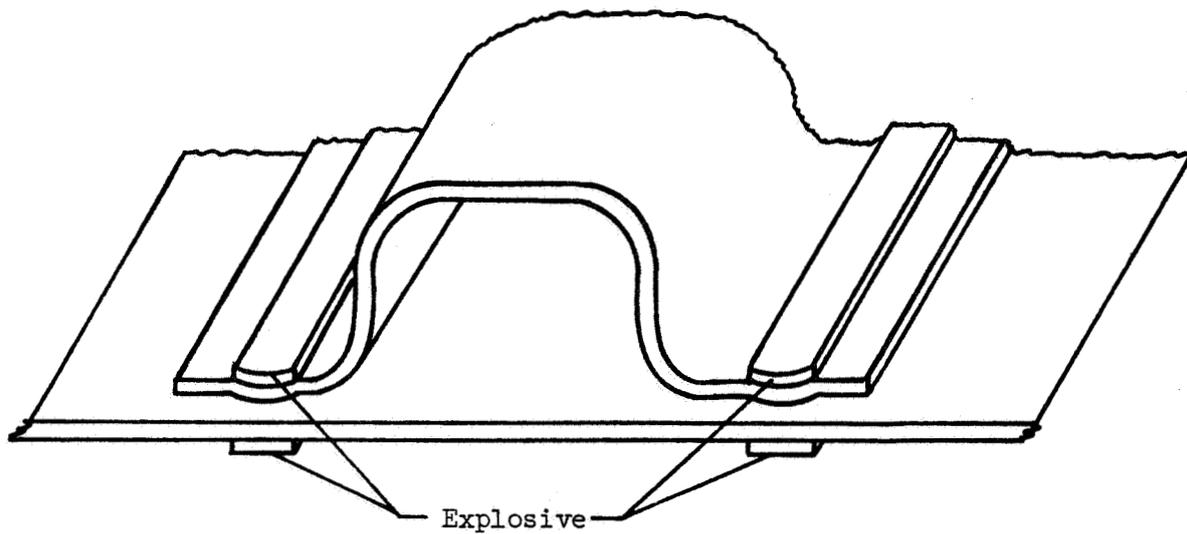


Figure 8.- Setup for explosive welding of titanium rib (without anvils).

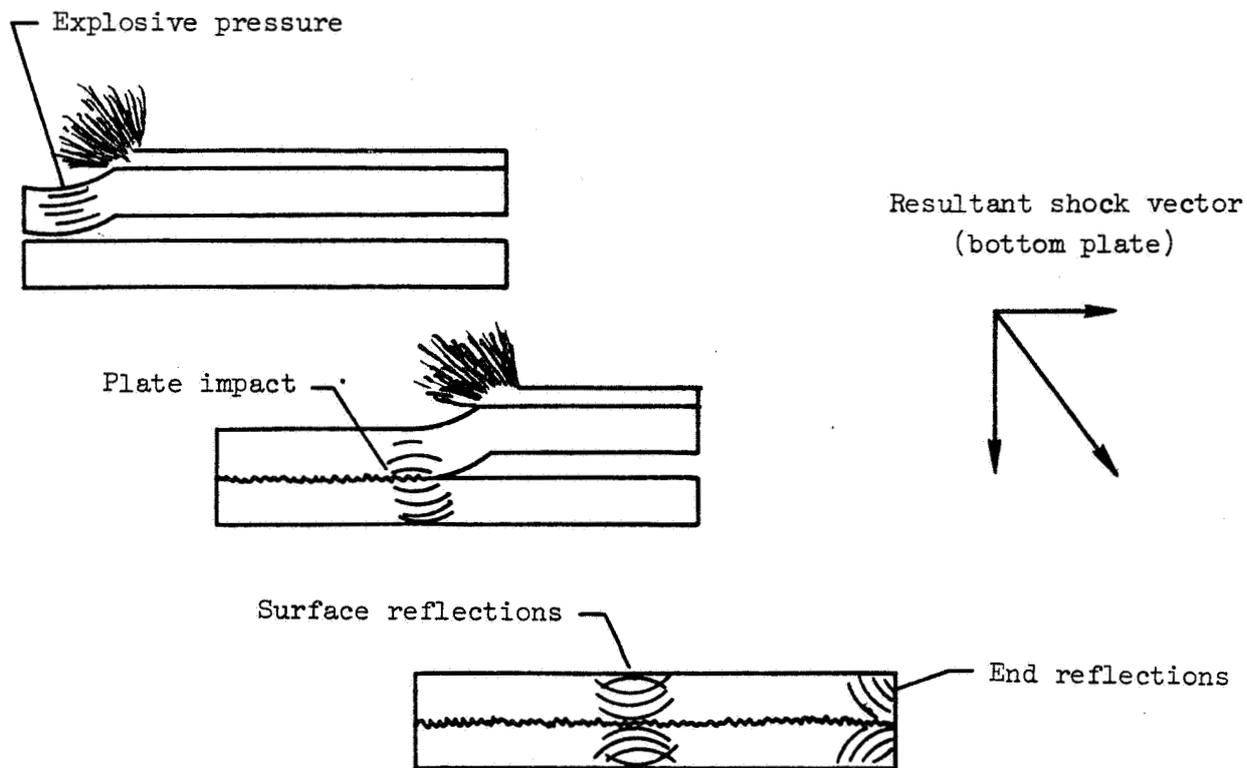


Figure 9.- Mechanical shock wave interference

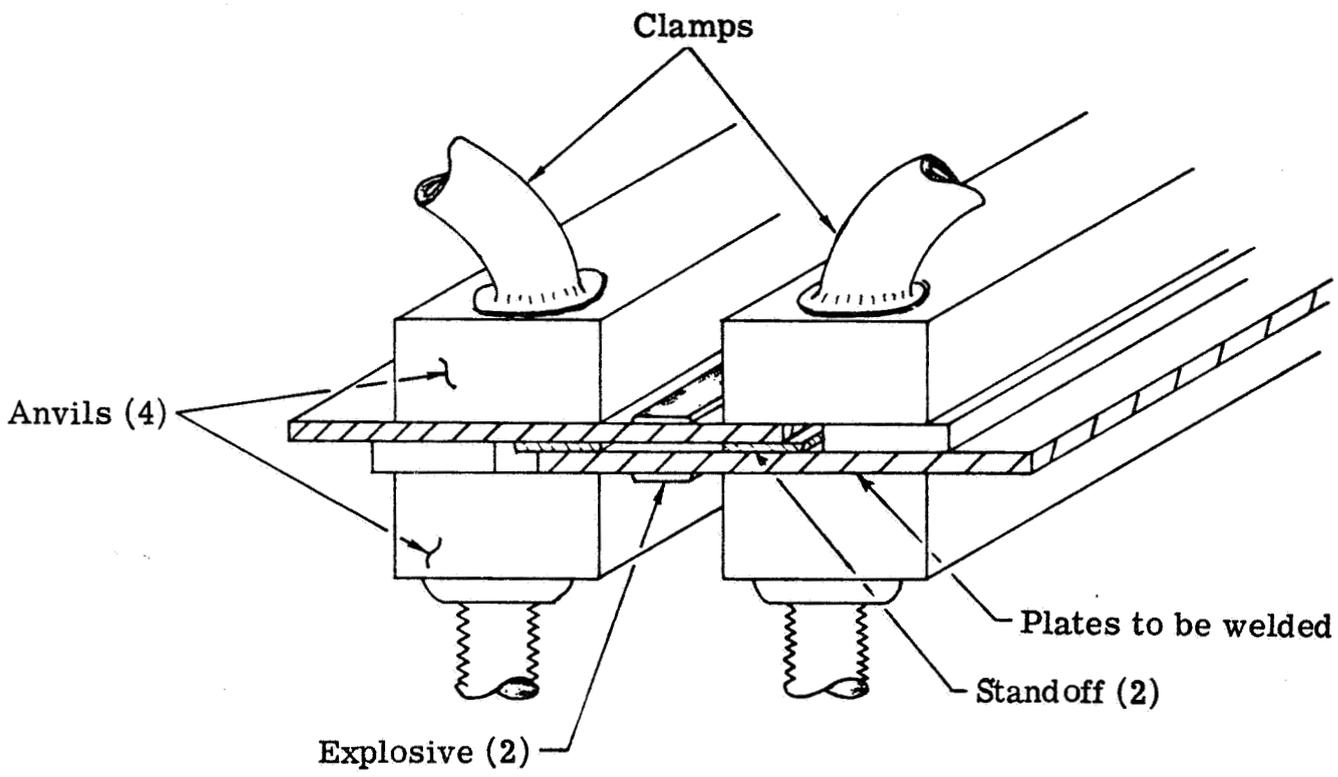
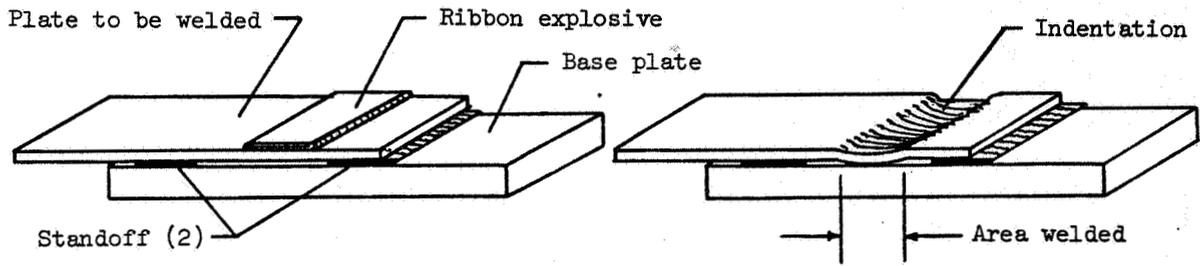
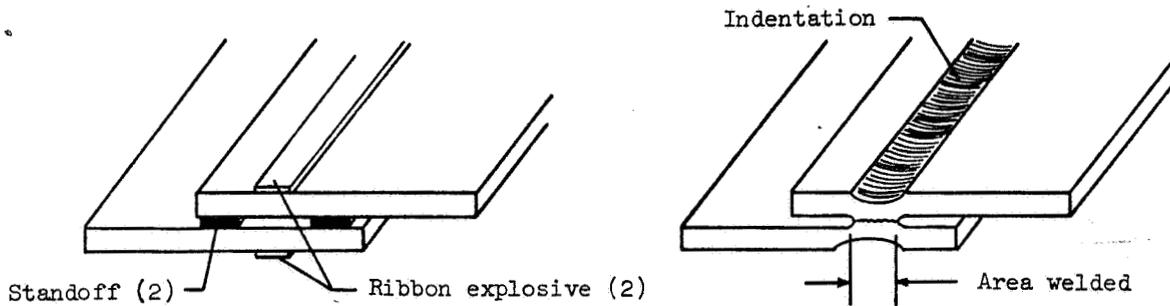


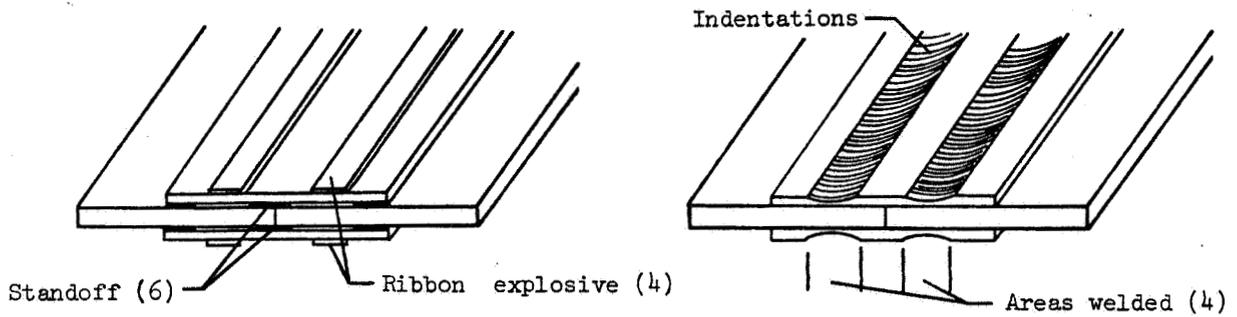
Figure 10. - Mechanical shock attenuation technique



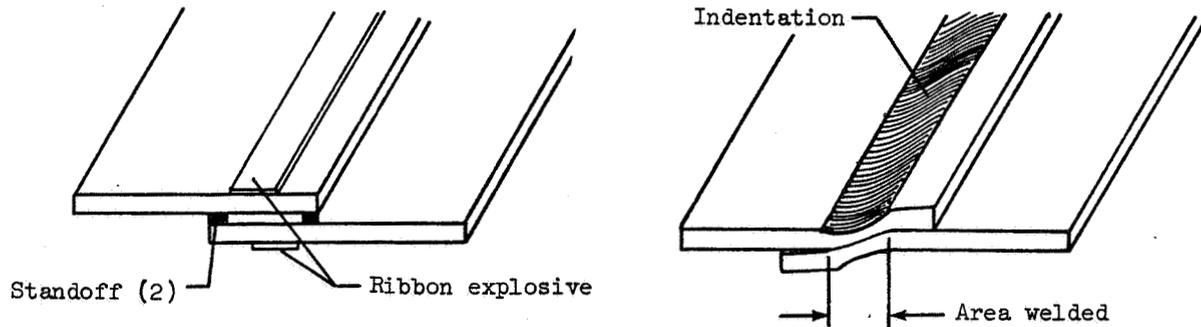
Dissimilar - thickness lap joint



Similar - thickness lap joint



Sandwiched - butt joint



Scarf joint

Figure 11.- NASA - LRC explosively welded joints.

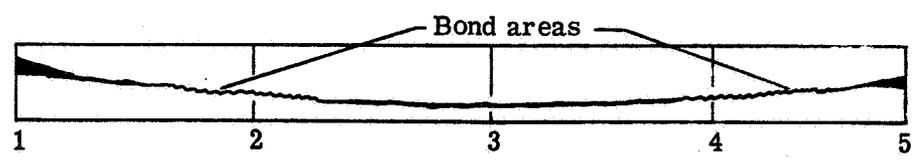
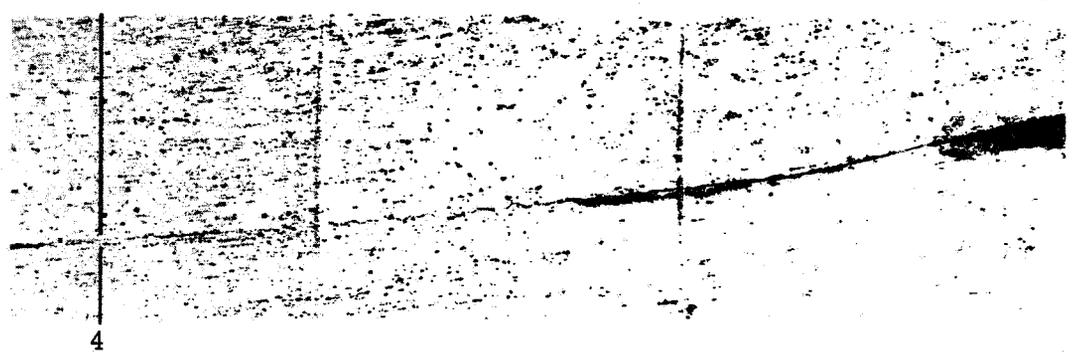
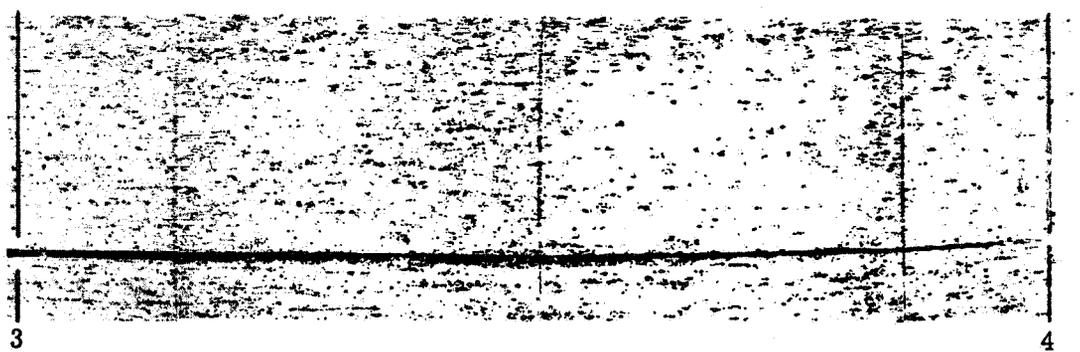
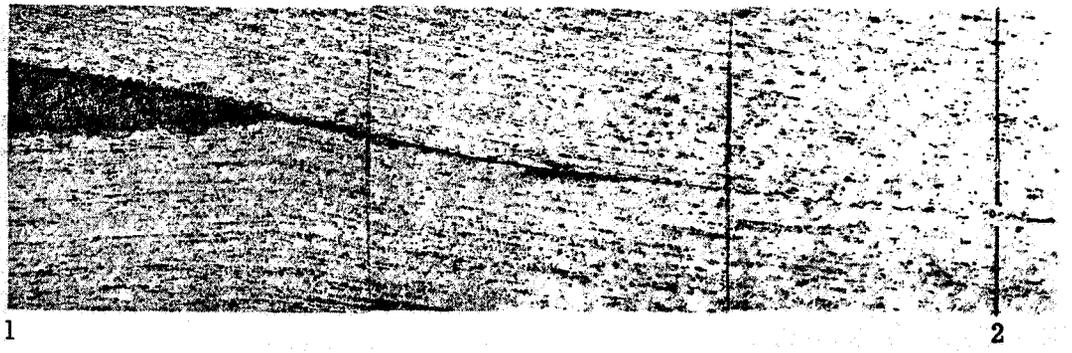
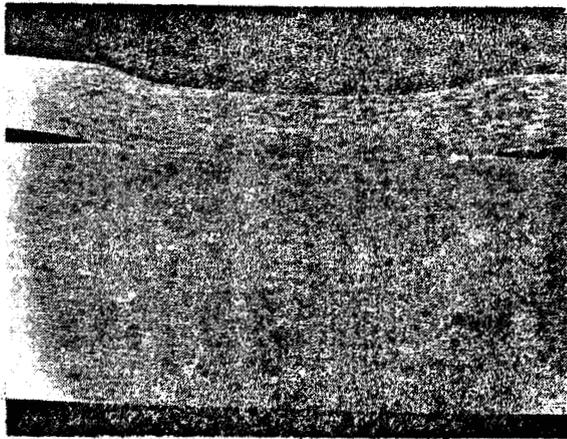
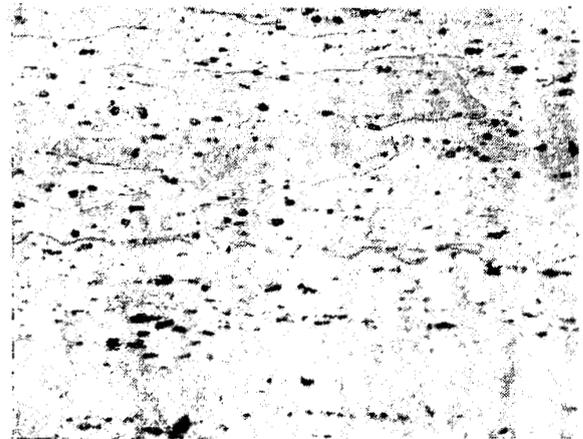


Figure 12. - Cross-section of a lap joint of 0.063" 7075-T6 to 0.25" 6061-T6, 54x



0.072" 2024-T4 to 6061-T6, 6.6x



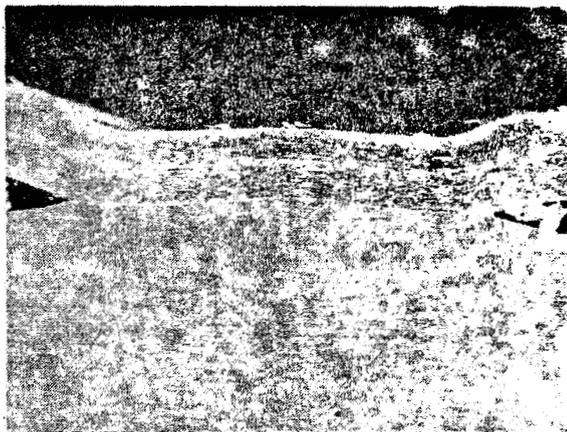
0.072" 2024-T4 to 6061-T6, 265x



0.063" 7075-T6 to 6061-T6, 6.6x



0.063" 7075-T6 to 6061-T6, 265x

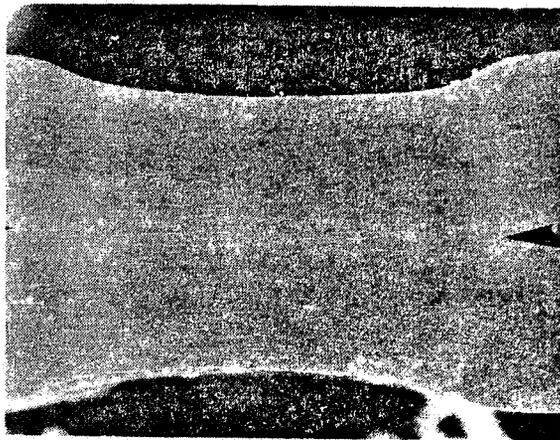


0.063" 2024-T3 Alclad to 6061-T6  
Inverted "V" Standoff, 6.6x

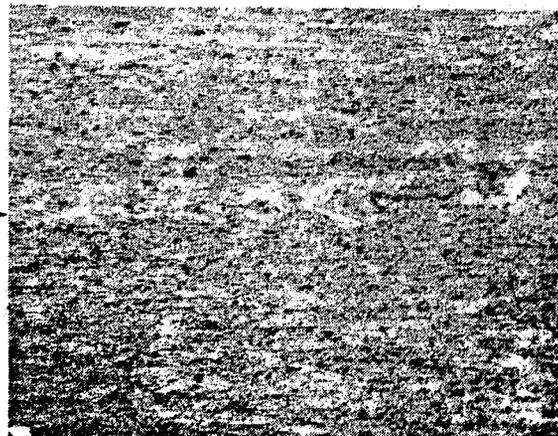


0.063" 2024-T3 Alclad to 6061-T6  
Inverted "V" standoff, 66x

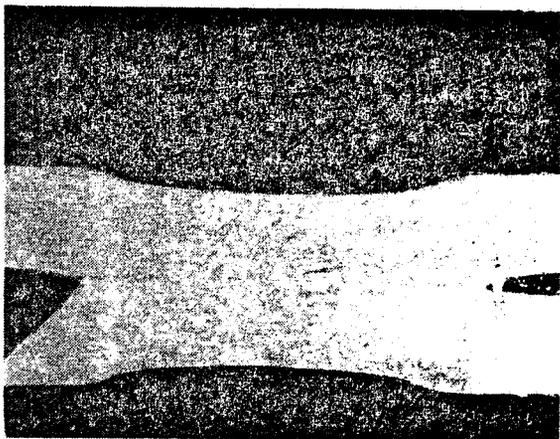
Figure 13. - Typical photomicrographic cross sections of dissimilar-thickness lap joints.



1/8" 6061-T6 to self, 6.6x



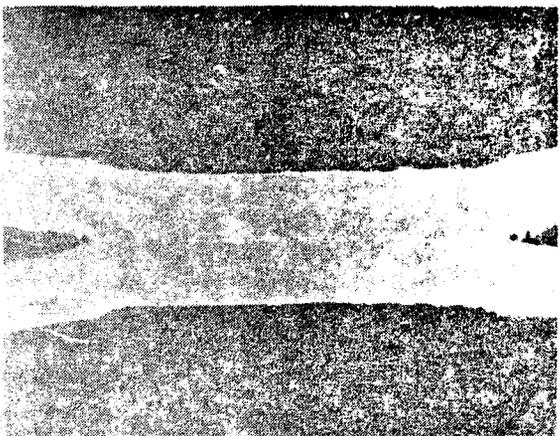
1/8" 6061-T6 to self, 77x



1/10" 2219-T31 to self, 6.6x



1/10" 2219-T31 to self, 265x



0.056" Ti-6Al-4V to self, 6.6x



0.056" Ti-6Al-4V to self, 265x

Figure 14. - Typical photomicrographic cross-sections of similar-thickness lap joints.

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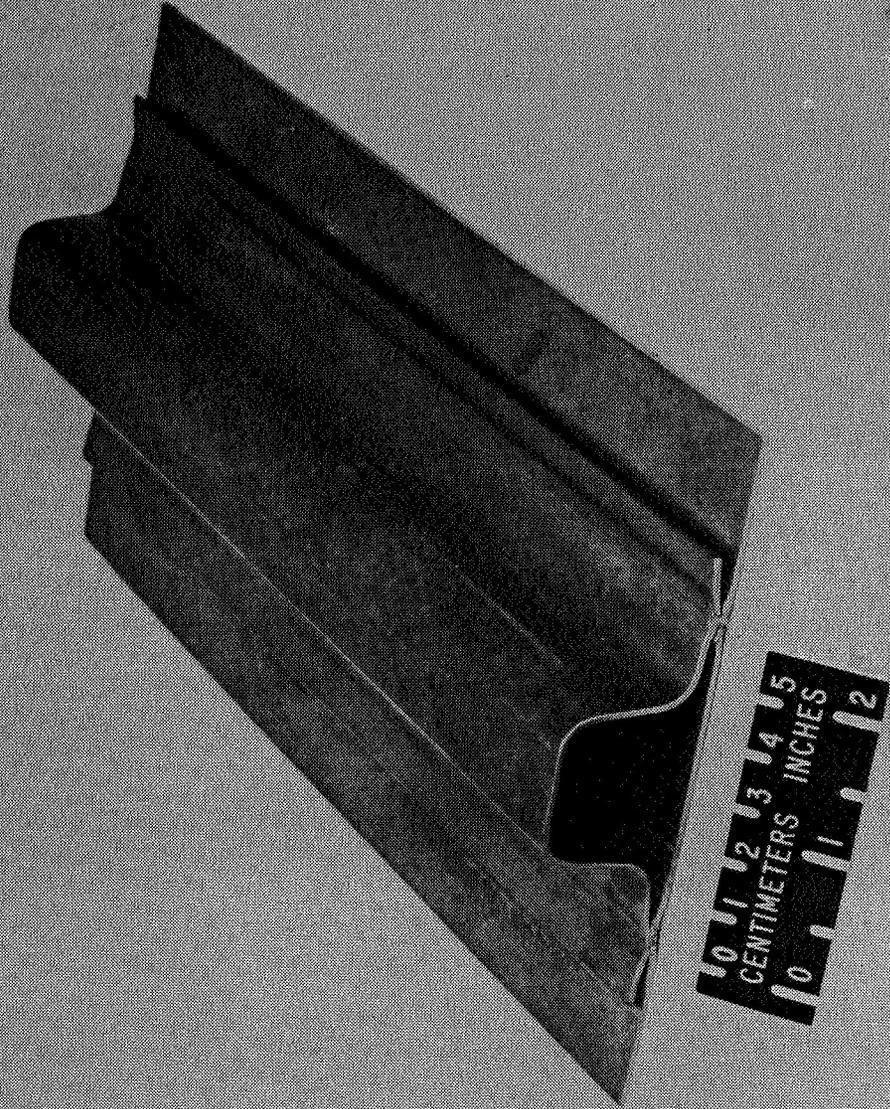
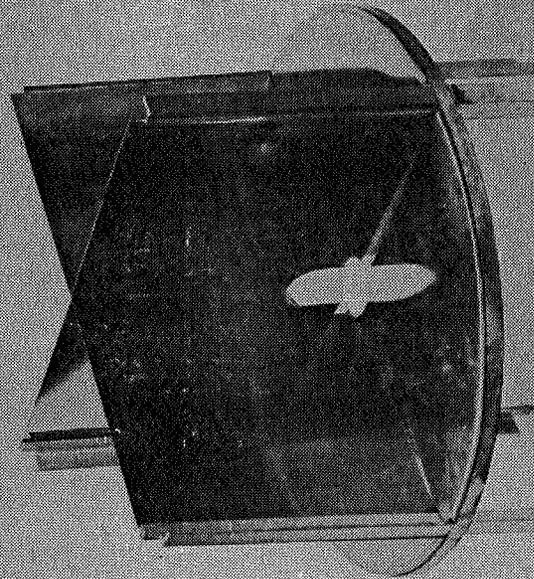
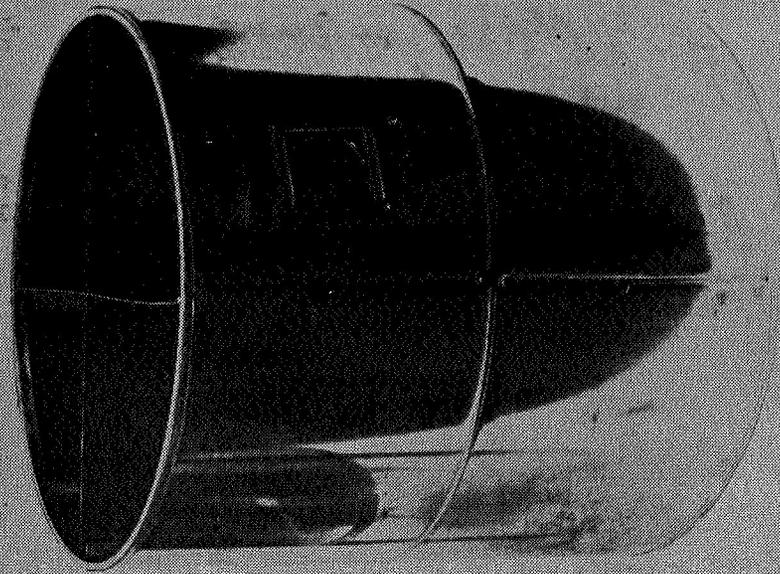


Figure 15.- Photograph of titanium rib section.

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**PHOTO**

Figure 16.- Photograph of 1/12 scale model of space station type structure; the internal structure of the model is shown on the left.

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